

## CLAIMS

What is claimed is:

- 1           1. A quantum dot vertical cavity surface emitting semiconductor laser  
2 (VCSEL), comprising:  
3           a first distributed bragg reflector (DBR) mirror disposed on a substrate  
4 layer comprised of a first plurality of mirror pairs with each mirror pair  
5 including layers having a step change in indices of refraction;  
6           a second distributed bragg reflector (DBR) mirror comprised of a  
7 second plurality of mirror pairs with each mirror pair including layers having a  
8 step change in indices of refraction;  
9           a semiconductor quantum dot active region disposed between a top of  
10 the first DBR mirror and a bottom of the second DBR mirror, the quantum dot  
11 active region including a plurality of quantum dots embedded in a plurality of  
12 quantum wells disposed proximate at least one antinode of a longitudinal optical  
13 mode, the quantum dots having a corresponding optical confinement factor;  
14           first and second doped semiconductor intracavity contact layers each  
15 having a thickness of no more than about half a wavelength disposed between  
16 the first and second DBR mirrors positioned and doped to inject electron-hole  
17 pairs into the quantum dot active region in response to a drive current;

18 the mirror pairs of at least one of the DBR mirrors comprised of a  
19 semiconductor layer and an oxidizable semiconductor layer which has been  
20 oxidized to form a material with a refractive index substantially lower than the  
21 unoxidized semiconductor, increasing the reflectivity of the mirror; and  
22 at least one mode control layer disposed between the top of the first  
23 DBR mirror and the bottom of the second DBR mirror forming a refractive index  
24 profile to increase optical confinement of the quantum dot active region and  
25 reduce optical confinement in the contact layers.

1 2. The VCSEL of claim 1, wherein the number of quantum dot layers,  
2 the optical confinement of the quantum dot layers, and an optical overlap in  
3 doped contact layers is selected to achieve a threshold gain that is less than a  
4 saturated gain of a ground state of the quantum dots over a temperature range  
5 between about 0 °C to about 85 °C.

1 3. The VCSEL of claim 2, wherein the active region has a longitudinal  
2 thickness that is about an integer number of half wavelengths in the laser at a  
3 target emission wavelength.

1 4. The VCSEL of claim 1, wherein each mode control layer has a  
2 longitudinal thickness of about one quarter of the emission wavelength in the  
3 laser, has a refractive index different than adjacent layers, and is positioned in the  
4 cavity to form a resonant reflection acting to increase the longitudinal mode

5 intensity in the quantum dot active region and decrease the longitudinal mode  
6 intensity in the contact layers.

1 5. The VCSEL of claim 4, wherein there is a first mode control layer  
2 disposed between a first end of the active region and the first mirror and a  
3 second mode control layer disposed between a second end of the active region  
4 and the second mirror.

1 6. The VCSEL of claim 5, wherein each mode control layer is disposed  
2 between an end of the active region and a heavily doped contact layer.

1 7. The VCSEL of claim 1, wherein the second DBR mirror comprises  
2 mirror pairs having an oxide layer and a semiconductor layer.

1 8. The VCSEL of claim 7, wherein the first DBR mirror comprises  
2 mirror pairs having a semiconductor layer and an oxidizable semiconductor  
3 layer with at least one opening is formed in the first DBR mirror through the  
4 oxidizable semiconductor layer to laterally oxidize the oxidizable layers with a  
5 laterally connecting portion of the first DBR mirror along at least one side of the  
6 first DBR mirror to inhibit delamination of the first DBR mirror.

1 9. The VCSEL of claim 1, wherein the at least one DBR mirror  
2 comprised of a semiconductor layer and an oxidizable semiconductor layer  
3 further comprises: an intermediate layer disposed between the semiconductor

4 layer and the unoxidizable semiconductor layer having a composition selected to  
5 inhibit delamination of the oxidized DBR mirror.

1 10. The VCSEL of claim 8, wherein the substrate is a GaAs substrate  
2 and the quantum dots comprise self-assembled InAs quantum dots formed in  
3 InGaAs quantum wells, and the DBR mirrors layers comprise alternating layers  
4 of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  and  $\text{Al}_y\text{Ga}_{1-y}\text{As}$ , where  $x$  is greater than  $y$ .

1 11. The VCSEL of claim 10, wherein the Al molar fraction of the  
2  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer is selected to be between about 0.95 to 0.99 whereby the  
3 oxidation rate of the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer is controlled.

1 12. The VCSEL of claim 1, wherein there is a first mode control layer is  
2 disposed between a first end of the active region and the first mirror and a  
3 second mode control layer disposed between a second end of the active region  
4 and the second mirror, each mode control layer having a longitudinal thickness  
5 of about one quarter of the emission wavelength in the laser, has a refractive  
6 index different than adjacent layers, and is positioned to form a resonant  
7 reflection acting to increase the longitudinal mode intensity in the quantum dot  
8 active region and decrease the longitudinal mode intensity in the contact layers.

1 13. The VCSEL of claim 12, wherein each mode control layer has a  
2 refractive index lower than adjacent layers.

1           14. The VCSEL of claim 13, wherein the active region has a thickness that is  
2           approximately an integral number of half wavelengths in the laser.

1           15. The VCSEL of claim 12, wherein each mode control layer has a refractive  
2           index higher than adjacent layers.

1           16. The VCSEL of claim 15, wherein the active region has a thickness that is  
2           approximately an odd number of quarter wavelengths.

1           17. A vertical cavity surface emitting semiconductor laser (VCSEL),  
2           comprising:

3                     a first distributed bragg reflector (DBR) mirror;

4                     a second distributed bragg reflector (DBR) mirror spaced apart from  
5           the first mirror to form a microcavity for a longitudinal optical mode;

6                     a semiconductor quantum dot active region having a first end and a  
7           second end disposed in the microcavity between the mirrors;

8                     first and second doped semiconductor intracavity contact layers

9           disposed in the microcavity on opposed ends of the quantum dot active region

10          doped to inject electron-hole pairs into the quantum dot active region in response  
11          to a drive current;

12                     at least one mode control layer disposed in the microcavity;

13                     the at least one mode control layer having a refractive index profile for

14          generating reflections within the microcavity which create a resonance condition

15 that increases optical confinement in the active region and decreases optical loss  
16 in contact layers.

1 18. The laser of claim 17, wherein each mode control layer is approximately  
2 a quarter of a wavelength in thickness and has a refractive index profile different  
3 than adjacent layers.

1 19. The laser of claim 18, wherein each mode control layer is disposed  
2 between the active region and a heavily doped portion of a contact layer.

1 20. The laser of claim 17, wherein at least one of the DBR mirrors is an  
2 ultrahigh reflectivity DBR mirror formed by laterally oxidizing DBR mirror pair  
3 layers that include an oxidizable semiconductor layer and a substantially non-  
4 oxidizable semiconductor layer.

1 21. The laser of claim 20, further comprising an intermediate composition  
2 layer disposed between the oxidizable semiconductor layer and the substantially  
3 non-oxidizable semiconductor layer to inhibit delamination.

1 22. The laser of claim 20, wherein the first mirror is formed into a mesa  
2 laterally oxidized along at least one side; and  
3 the second mirror has its bottom surface disposed on a substrate layer,  
4 the second mirror having at least one cavity disposed through it through which  
5 the second mirror is oxidized and at least one connecting section providing  
6 lateral support.

1           23. The laser of claim 21 wherein the laser has a threshold gain less than a  
2   saturated gain of a ground state of the quantum dots in a temperature range  
3   between about 0 °C and 85 °C.

1           24. A vertical cavity surface emitting laser, comprising:  
2               first and second distributed bragg reflector (DBR) mirror means for  
3   forming an optical cavity between the mirror means having optical feedback;  
4               quantum dot active means disposed within the optical cavity for  
5   providing optical gain responsive to a current;  
6               intracavity contact layer means for providing current to the quantum dot  
7   active means; and  
8               resonant mode control layer means disposed between the mirror  
9   means for increasing the optical confinement of the quantum dot active means  
10   and reducing the optical intensity in the contact layer means.

1           25. The laser of claim 24, further comprising:  
2               delamination inhibition means for inhibiting the delamination of the  
3   high reflectivity mirror means.

1           26. The laser of claim 24, wherein a threshold gain of the laser is less than a  
2   saturated ground state gain over a temperature range between about 0°C to  
3   85°C.

1        27. A method of forming a vertical cavity surface emitting laser having an  
2 oxidized bottom distributed bragg reflector (DBR) mirror with lateral support,  
3 comprising:

4        etching at least one opening into mirror layers of the bottom DBR mirror,  
5 the at least one cavity disposed proximate an outer perimeter of a lasing portion  
6 of the bottom DBR mirror with at least one lateral connecting portion of the  
7 mirror layers remaining to support the lasing portion of the mirrors; and  
8        laterally oxidizing the mirror layers of the bottom DBR mirror.

1        28. The method of claim 27, wherein the bottom DBR mirror includes  
2 AlGaAs layers and the mirror layers are oxidized in steam.

1        29. The method of claim 28, wherein the mirror layers comprise AlAs/GaAs  
2 layers laterally oxidized to AlO/GaAs.

1        30. The method of claim 29, further comprising an intermediate  
2 composition layer disposed between the AlAs and GaAs layer.

1        31. The method of claim 30, wherein the AlAs layer comprises a molar  
2 fraction of gallium of at least about 0.01 for improved control of lateral oxidation  
3 rates.

1        32. A vertical cavity surface emitting laser fabricated by the method of  
2 claim 27.



1           33. A method of forming a vertical cavity surface emitting laser with  
2     intracavity contacts from a substrate having a top DBR mirror with DBR mirror  
3     layers, a bottom DBR mirror with DBR mirror layers, a top contact layer, an  
4     active region, and a bottom contact disposed between the mirrors, the method  
5     comprising:

6           etching a top mirror mesa to expose the top contact layer outside of a top  
7     mirror for the VCSEL;

8           masking the top mirror mesa and etching down to the bottom contact layer;

9           etching at least one opening into mirror layers of the bottom DBR mirror,  
10    the at least one opening disposed proximate an outer perimeter of a lasing  
11    portion of the bottom DBR mirror with at least one lateral connecting portion of  
12    the layers remaining to support the lasting portion of the mirrors; and

13          laterally oxidizing the mirror layers of the bottom DBR mirror through the  
14    at least one opening.

1           34. The method of claim 33, further comprising: depositing a top contact  
2     metallization on a portion of the top contact forming a metal contact on the top  
3     contact layer about the top mirror mesa leading to a contact pad prior to etching  
4     down to the top contact layer.

